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PROPELLERS AND HELICOPTER BLADES OF FIBER-REINFORCED SYNTHETIC RESIN MATERIALS

Ulrich Huetter

Translation of: "Luftschrauben und Hubschrauber-Rotorblaetter aus faser-verstaerkten Kunstharzen," Jahrbuch, 1960 der WGL, pp. 374-381.

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16. Abstract
Shell structures for propellers and helicopter blades are predominantly under centrifugal loads and therefore essentially subjected to such extensive radial stresses that full advantage can be taken of the high tensile strength of strand-reinforced synthetic resin materials.

Great difficulties have been encountered in the past with the diffusion of end loads into fiberglass reinforced compound materials. These difficulties, however, can be overcome by applying the loop method, a method by which the diffusion into various strands is accomplished by means of loops formed by continuous layers of strands.

By special treatment of the strands before being placed into the mould, any arbitrary distribution of thickness of the shells can be achieved without using special jigs. The application of various manufacturing techniques to the manufacture of aerofoils in large interla flow engines, propellers and helicopter blades is illustrated.

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PROPELLERS AND HELICOPTER BLADES OF FIBER-REINFORCED SYNTHETIC RESIN MATERIALS*

Ulrich Huetter**

1. Orthotropic Composite Materials /374***

Most composite materials having a fiber structure are primarily orthotopic. This orthotropic property applies for small space elements of the material for all fiber arrangements.

By making a layered structure, by crossing the material of several orthotropic plates like plywood or by weaving the fibers before the imbedding mass is applied, it is possible to at least approach two-dimensional isotropic conditions. However, usually the losses in the weight-specific material strength and stiffness is so great that the typical advantages of the initial materials no longer are exploited.

On the other hand, the isotropic property of the material is not at all required in many construction elements in light structures. By a clever configuration, it is possible to produce local orthotropic conditions and it is permissible to have weight and stiffness penalties for the overall design. Examples of this are the classical cabinet maker constructions,

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***Numbers in the margin indicate the pagination of the original foreign text.

which considers the special feature of high quality but orthotropic wood material in an exceptionally clever way.

Materials which are made of high quality fibers imbedded in cold-hardened resins are superior to wood. They offer the possibility of controlling the fiber direction during the manufacture of the light construction elements, which means that the three-dimensional curvature and cross section variation can be almost arbitrarily selected.

Components stressed in one preferred direction often occur in aviation construction. One must only think of the flanges in the spars of wings and control surfaces, as well /375
as the shells of the blades of propellers, of helicopter rotors and the blower blades of vertical takeoff and hovering devices.

For these applications, fiber materials seem to be predestined, not only because of their superior breaking length and the additional safety for unpredictable excessive rotation rates, but also because of their advantages during the manufacturing process.

2. The Strength of Glass Fibers

For fibers made of boron silicate or E glass with a low alkali content, it is known that there is a statistical relationship between the elementary thread diameter and the tensile strength, for the commercial grades. The smallest fibers have the highest strengths (Figure 1).

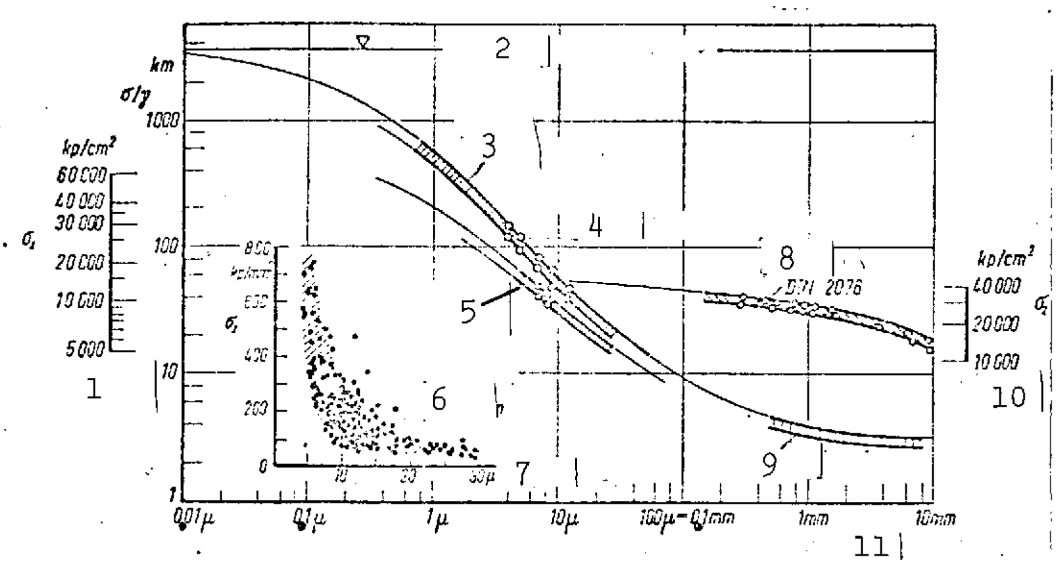

Figure 1. Tensile fracture stress σ_z and crack length σ/γ referred to it of spring steel wire as well as of glass fiber threads manufactured in industry and in the laboratory.

1- glass resin; 2- theoretical-atomic cohesion forces; 3- glass silk threads, alkali content 0.5 to 1%; 4- measured values of W. Otto, 1955; 5- glass silk threads, alkali content 8 to 10%; 6- scatter of individual fibers; 7- fiber diameter; 8- spring steel wire; 9- ordinary glasses; 10- steel; 11- fiber diameter.

This phenomenon has been investigated many times over the last forty years, primarily because theoretical derivations based on atomic bond forces predicted glass strengths within the SiO_2 lattices which are many times those values established to be the maximum strengths of elementary fibers.

In 1955, W. H. Otto [1] and in 1958 W. F. Thomas [2] showed that the assumed dependence of the statistical values of the elementary thread strength on the diameter can no longer be found when the fibers are produced in dried purified air, and when a correspondence is established between the temperature of the melt and the drawing velocity of the threads.

Thomas found a constant elementary thread strength of 36000 kp/cm^2 over a diameter range between 5 to about 16 μ for fibers with which he performed drawing experiments. These results were later on confirmed with glass rod dimaeters of up to 3 mm [3]. This makes one believe that the hypothesis established in 1936 by A. Smekal [4] regarding the arbitrarily distributed defects with various degrees of local surface damage is to be attributed to manipulations during the manufacturing process which are difficult to avoid.

Two conclusions can be drawn from this:

1. The increase in the statistical elementary thread strength with decreasing fiber diameter and for a given sample length in any strength test is a consequence of the smaller probability of the occurrence of certain surface damage.

2. A. Boldt* first made some assumptions because of experiments he was preparing. According to this, the dependence of the composite strength of the glass fibers in strands or cloths should not depend as much on the thread diameters, as was the case in experiments using single threads.

3. The Behavior of Resins

One important advantage of glass threads over metallic materials is that they show an almost linear stress-strain behavior up to fracture, so that there are no clear limits such as the proportionality limit or the yield limit. Without

*During the plastic meeting in Essen on May 17, 1960, a hypothesis was formulated regarding the influence of the elementary thread diameter on the strength of fiber-reinforced components during the discussion.

experiencing residual form changes, they can be practically loaded up to separation.

However, for composite materials, there are limitations because of the behavior of the polyester and epoxy resins when they are subjected to loads (Figure 2). Even for relatively small loads, they have a non-linear stress-strain behavior and creep under loads even at relatively low temperatures. Many authors W. N. Findley [5] were able to show that simple dynamic models can be given to interpret the deformation-time behavior of such materials.

These phenomena, the nonlinearity of the stress-strain diagram and the creep of the supporting material, have many consequences for the cohesion of the composite material. For example, even if a rod is loaded along a single axis, there is a gradual decrease of the stress in the resin, as the dash-dot line in Figure 2 shows.

This behavior is objectionable because of the danger of delamination. However, it only indirectly affects the loadability of the composite material, because the stresses in the resin are /376 only 2 to 3% of the values which are reached in the glass, if the deformations in the glass and the resin are the same. However, the thrust is almost exclusively taken up by the resin. Unfortunately, it is also very small compared with the strength of the glass fibers.

Not much is known at the present time about the adhesion between the glass and the resin. Certainly it is much smaller than the tensile strength of the resin, because all fractures of composite material are introduced by delamination phenomena, which can also be seen macroscopically because the samples become white and there is local fiber separation.

For the designer, all this means that it is necessary to carefully design components with high specific loads, so that the fibers will lie in the direction of the largest principal stresses. Also the ellipsoids which represent the local stress tensors referred to the principal axes, must be sufficiently large.

It is easy to see that negative stresses, that is pressure from all sides in the planes perpendicular to the fibers, is especially favorable. This is one fact which we were able to exploit when designing the connection flanges of our rotors.

4. High Glass Content for Strand Reinforcement

Because the resin strength is small for uniform strain, the strength and stiffness of the material depend greatly on the cross section fraction of the fiber material, as is well known. Therefore, one wishes to increase the glass content up to close to the geometric limit specified by the circular cross section of the glass fibers. However, since the viscosity of the resins is large and not very uniform, and because the excess resin which penetrates during emersion of the fibers must flow away between the fibers as the glass content increases and the gap separations become smaller (Figure 3), this is not a very simple matter. Especially the time required for preparing the material is quite extensive for very high glass fractions. This is also true for cloths, as for strand reinforcement.

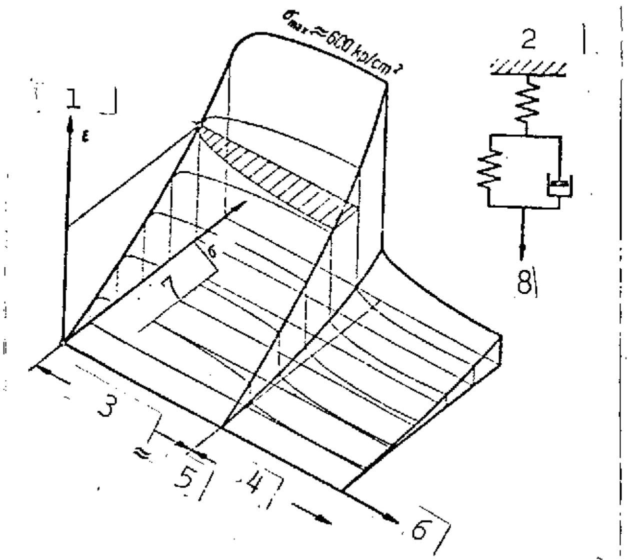

Figure 2. Time-stress-strain diagram of polyester resin.

1- strain; 2- dynamic models; 3- loaded; 4- unloaded; 5- 10 minutes; 6- time; 7- stress. 8- load P

One disadvantage of strand reinforcement is that it is not possible to avoid non-uniformities of fiber density over the cross section, a phenomenon which all micro-sections of rods with high glass content show. This is, of course, unfavorable for the strength of the components.

A method has been developed for pressing out the resin excesses after immersion

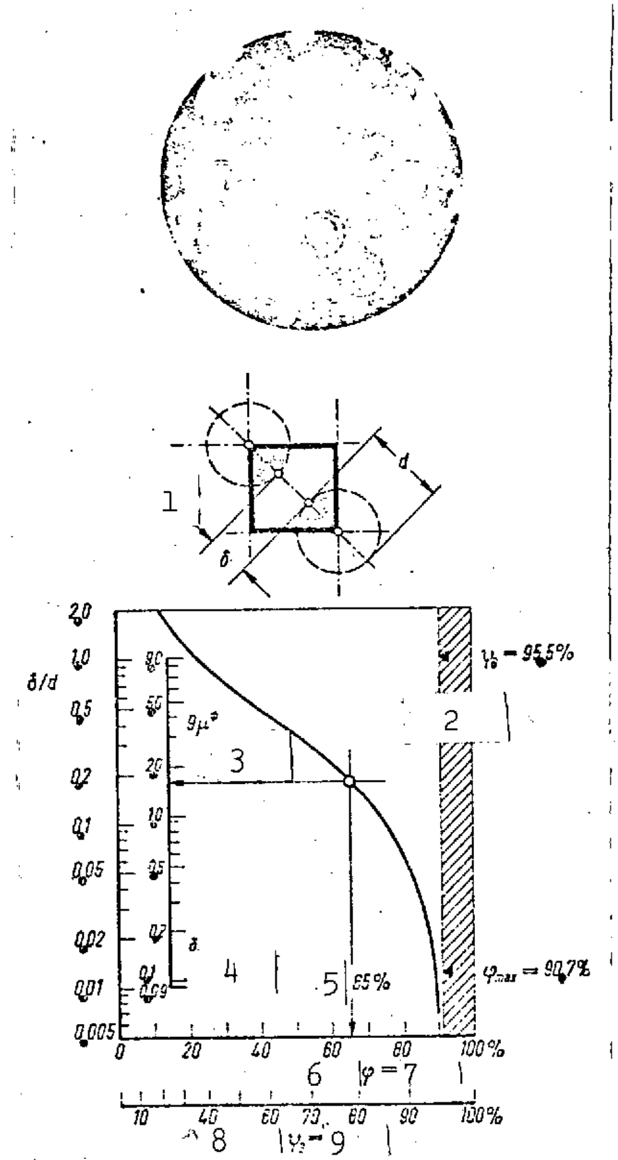

Figure 3. Relationship between average distance (crack size) and average glass content of compound material.

1- crack size; 2- geometric limit of glass proportion; 3- elementary fiber thickness; 4- crack size; 5- for example; 6- glass volume fraction; 7- V_{glass}/V_{thread}; 8- glass weight fraction; 9- G_{glass}/G_{thread}.

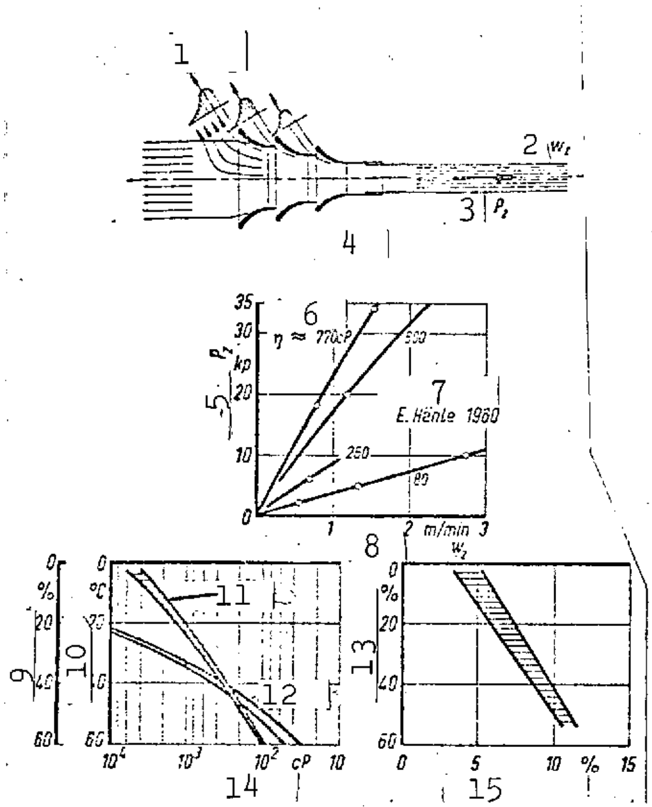

Figure 4. Influence of styrene content and temperature of polyester resin on its viscosity and volume shrinkage and dependence of the required tensile force on the pulling rate and resin viscosities during the manufacture of threads in multistage nozzles.

1- exit velocity of the resin; 2- pulling velocity; 3- pulling force; 4- pulling nozzle; 5- pulling force; 6- resin viscosity; 7- nozzle pulling experiments; 8- pulling velocity; 9- styrene content; 10- temperature; 11- temperature influence; 12- styrene influence; 13- styrene content; 14- resin viscosity; 15- volume shrinkage.

of the reinforcement material. In this process, the fiber strands (rovings) are drawn through a number of nozzles separated by rings with holes, for removal of the excess resin, which is done after the material has been emersed in the immersion bath [6].

In order to hold down the time for the glass accumulation process, high drawing rates are desirable. Of course, the only limitation is the required pulling force, which is the result of the pressures which the nozzles apply to the strand. These pressures cannot be arbitrarily increased, because otherwise the peripheral elementary fibers will tear because of friction forces or at least will be locally damaged.

Extrusion pressures and tension forces applied to the strands are independent of the drawing velocity and the viscosity of the resin (Figure 4). This means that the drawing could be accelerated by reducing the resin viscosity, for example, by increasing the styrene additive in polyester resins. However, /377 one would then have to accept a considerable increase in the volume shrinkage during polymerization. This increased shrinkage compromises the form of the components, the adhesion between the glass and the resin, and the humidity resistance of the components. Epoxy resin is more expensive than polyester and is always preferred because of the smaller shrinkage in all cases where a good adhesion between the resin and the glass is important (for epoxy, it is only 2%, compared with 3 — 5% for polyester resins).

A reduction of the viscosity by heating the resins can only be carried out when the related considerable acceleration of the hardening process is acceptable, i.e., when the material is introduced into the mold so fast that this process is brought to a conclusion before the gelling process has begun.

Of course, it is natural to reduce the preparation times for the material by several multiple nozzles operating in parallel when a single mold is being filled. It then also becomes easier to control the gradual "rising" of the relatively large strands if the glass content is high.

5. Cloths and Mats

In the case of cloths and mats the accumulation occurs by pressing the emersed cloth pieces between rollers before they are inserted in the mold. It is also possible to use high compression pressures in the mold.

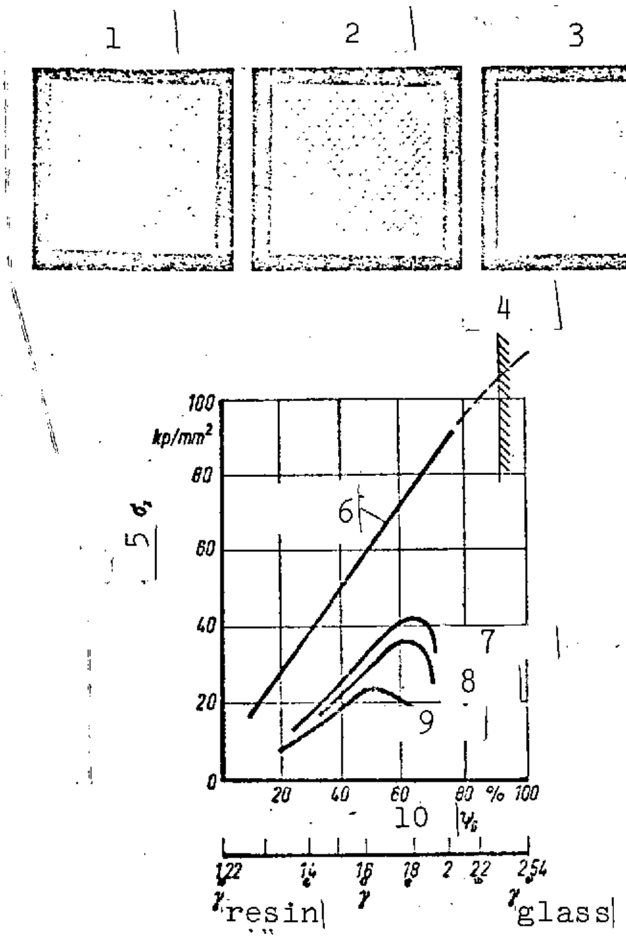

Figure 5. Tensile strength of samples of various compound materials as a function of glass weight fraction.

1- mat; 2- linen; 3- one-directional cloth; 4- theoretical limit; 5- tensile strength; 6- roving threads; 7- unidirectional cloths; 8- linen; 9- mat; 10- glass fiber content.

However, at high pressures, the elementary fibers will fracture at the crossing points of the threads, and the strength of the composite material decreases. Therefore, the optimum glass content for these extremely convenient reinforcement materials is limited to a maximum of between 50 and 60 weight percent (Figure 5).

Therefore, only cloths, especially those with linen bond, can be used as the outer layers of strand-reinforced components because of the quasi-isotropic and denser matrix. Cloth-reinforced shells are considerably inferior to those made of light metals as far as the stiffness per unit weight and buckling behavior are concerned. Also, difficulties occur in the introduction of the forces from the cloth structure of the reinforcement material, which are difficult to solve.

As is well known, the materials made up of strands are more favorable in this regard. It is primarily their tearing length and working capacity per unit weight which are superior to other materials by a considerable margin. A comparison of these characteristic numbers with those of high quality light metal alloys will demonstrate this.

It was E. J. Zeilberger and J. H. Lieb [7] who reported in 1959 (Table 1) that the E modulus of glass can be increased to 1.8 times the values of boron silicate glasses poor in alkali by adding beryllium oxide as a grid forming agent.

It is not important that the costs of such fibers is extremely high at the present time. Already, in a predictable amount of time, it will certainly become possible to use fiber composite materials which will have 2.5 times the tear length and at least eight times the specific working capacity of the best metallic materials. Also, they are 30% stiffer.

TABLE 1

Specific characteristic numbers* per unit weight		Boron silicate glass	Beryllium oxide glass
tear length	σ/γ	2,40	
stiffness	E/γ	0,73	1,32
eigen frequency	$E^{1/2}/\gamma$	0,98	1,30
plate buckling $(2 < n < 3)$	E/γ^{n}	1,24	2,22
work capacity	$\sigma^2/2E\gamma$	8,40	

*These numbers give the ratios of the glass fiber reinforced artificial materials and the values of the corresponding aluminum alloys Al7075. They apply for elementary thread diameters of 9 μ and a 72 weight percent glass content.

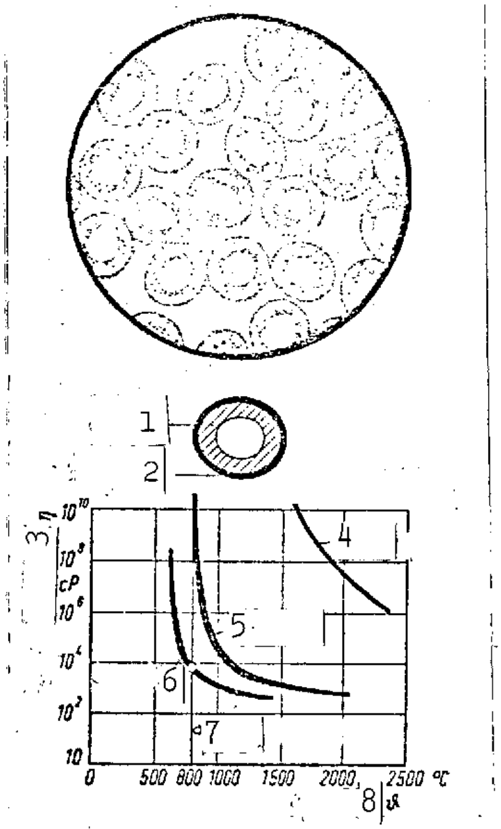

Figure 6. Fine glass silk tubes, drawn from two different types of glass. Suggestion of the brothers Dietzsch, Wiesbaden.

1- glass type A; 2- glass type B; 3- dynamic viscosity; 4- quartz glass; 5- glass type A; 6- glass type B; 7- sintering temperature; 8- temperature.

6. Hollow and Two-Material Glass Fibers

Another way of increasing the stiffness per unit weight to the level of the values for light metals, consists of doing away with resin altogether as the supporting material.

The brothers Dietzsch, Wiesbaden have, for some time, been manufacturing very fine hollow fibers made of synthetic materials. They have already drawn polyamide threads (Ultramid B) with a diameter of 10 μ. In conjunction with P. A. Koch, Krefeld, they have drawn two-material layer fibers (Figure 6).

If additional experiments show that it is possible to draw very thin hollow glass out of glass with different viscosity-temperature variations, it would then become possible to produce a material which would have a structure very close to that of wood. After a sintering process, this would result in two-material hollow glass threads which would be closely packed in heat-resistant molds.

It would then only be necessary for the softening point of glass type B, which makes up the outer layer, be somewhat lower than that of glass type A of the core, so that only the outer layer becomes soft during the sintering.

One certain disadvantage of such methods is that a considerable apparatus is required and the flexibility in forming the components which occurs with resin imbedding because of open molds, insertion without pressure, and low temperatures, even for the smallest numbers of components, will become lost.

7. Compression Strength in the Strand Direction

Elementary fibers imbedded in resin when subjected to compression loads in the fiber longitudinal direction will deviate to the side perpendicular to the load direction within the imbedding mass. The elastic transverse support of the fibers depends on the packing density and, therefore, on the glass content, as well as on the position of the individual fibers within the rod, that is, whether the fiber is at the edge or in the center.

Wave-shaped evasion figures with certain frequencies develop which propagate starting at a certain arbitrary point and run perpendicular through the rod. These then introduce the fracture via delamination processes. This phenomenon is, at the present time, being studied at the Institute for Aircraft Construction at the Institute of Technology, Stuttgart, in order to make evaluations of pressure loaded flanges and shells.

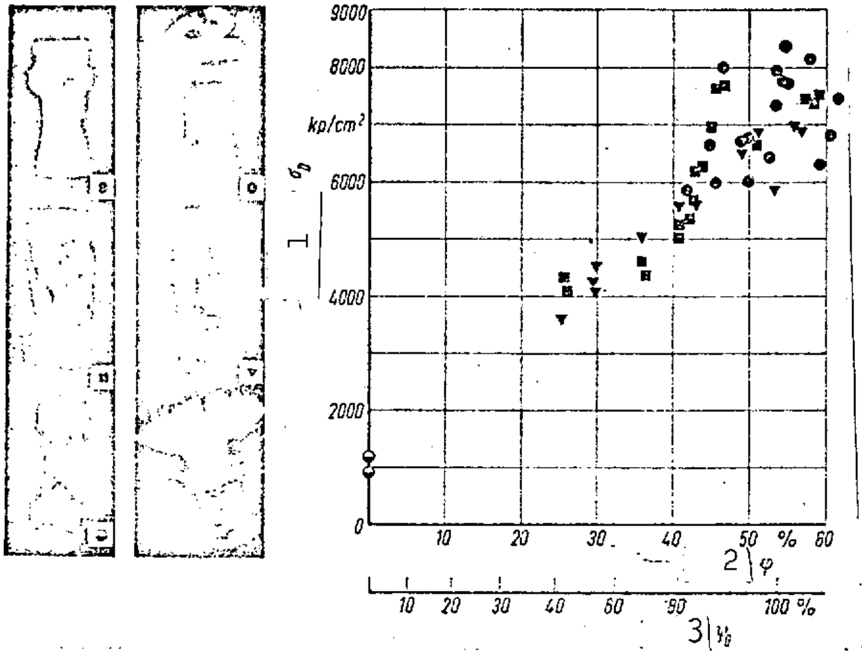

Figure 7. Compression stength of samples made of strand-reinforced polyesters with strand-bandaged heads. Slenderness of the rods with a square cross section 1:5.

1- fracture stress; 2- volume fracture; 3- glass fraction in weight percent.

As an intermediate result, we have developed requirements for introducing forces to compression samples (avoidance of fiber formation at the sample heads by means of strong bandages secured against longitudinal motion). Also, we have developed an experimental proof of the relationship between the pressure strength and glass content, which corresponded to the theoretical expectations (Figure 8).

8. The Alternate Load Strength of Rods Made of Glass Fiber Resin

In the case of oscillating loads, strand-reinforced low pressure resins behave like metals. It is only the fact that the relatively high material damping is exclusively produced by the resin and that glass and resin are both poor heat conductors,

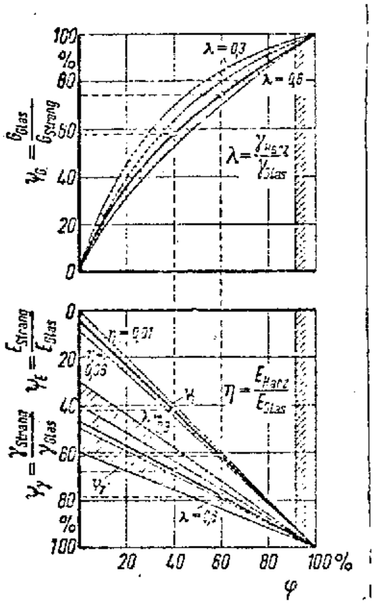

Figure 8. Glass weight fractions Ψ_G, ratio of elastic moduli Ψ_E, and ratio of specific weights Ψ_γ of the strand material, referred to the values for glass, as a function as glass volume fraction. The parameters are the ratios of the specific weights λ and the elastic moduli η of resin to glass. (Glas = glass; Strang = strand; Harz = resin).

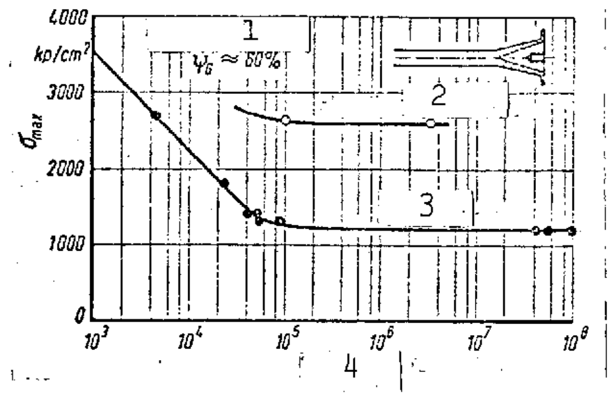

Figure 9. Woehler curves of strand-reinforced material for swelling tensile loading and for alternate bending loading.

1- glass weight fraction; 2- swelling tension loading; 3- alternate bending; 4- number of load changes.

which can lead to difficulties. This is because the internal heating of the samples can rapidly reach the temperature limits at which the resin loses its original strength.

In the case of tensile, compression, and alternating load samples with cross sections between 2 and 3 cm^2 (Figure 9), it was possible to hold down the temperatures using a cooling blower at working frequencies at about 30 Hz. In the case of propellers and helicopter rotors, such cooling would be directly obtained because of the high incident flow velocities.

9. The Construction of Large Rotor Blades

A method has been developed with E. Haenle, 1957, for constructing large wind turbine blades [6]. This method has been used to construct helicopter main and auxiliary rotors, propellers, braking air propellers, etc. These were designed in the form of foam supported shell bodies with attachment flanges and were made of continuously arranged strand loops next to each other (Figure 10).

The design of the connection in the form of an integral flange is the result of the designs of the bearing rings, the metallic opposing flange. The rings press down on the heads of the attachment screws. They experience a prestress because of the pressure perpendicular to the fiber direction (Figure 11) in the region of maximum stress.

Since the cross sectional form of the strands can be selected quite arbitrarily during the positioning process, it is natural to make the flange height so great that the bearing pressure in the bolts and the non-uniformity of the tangential /379 stresses in the eyebrows will remain within acceptable limits.

In order to obtain smooth outer surfaces without any reworking, the construction molds are made in the form of matrices. The upper and lower shells separate in surfaces through the jets. The straight generating lines of the separating surfaces approximately run in the chord direction of the profile skeleton lines, perpendicular to the blade radius.

Figure 10. Flange made of strand loops in the raw state.

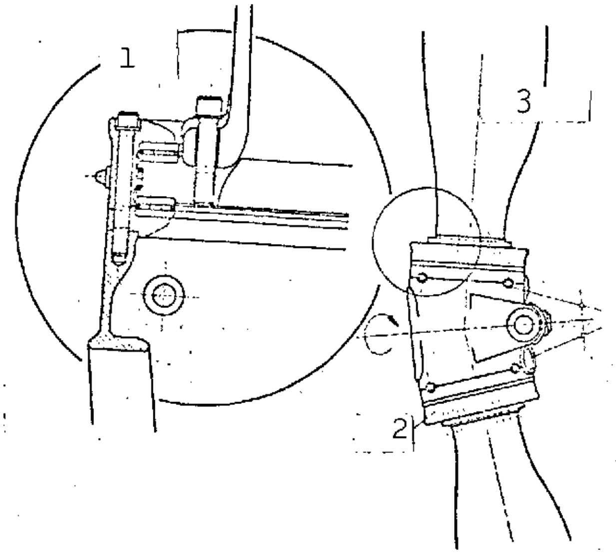

Figure 11. Cross section through the hub of a wind turbine rotor with a diameter of 34 m. The opposing flange is the carrier of the hardened bearing rings of the plane roller bearing.

1- plane roller bearing; 2- steel hub; 3- glass fiber-reinforced plastic blade.

In general, the separation surfaces are twisted. In the case of unrestricted helicopter rotor blades, of course, these are planes. In any case, the straight generating lines make it possible to accurately line up the separation surfaces before the partial shells are glued together. /380

The mold body consists of an artificial rock layer applied to a frame made of perforated sheetmetal and includes heating grids which are imbedded in the artificial rock. In this way, the polymerization is accelerated after the material is introduced, if this is desired.

The resin-saturated, soft and very flexible strands are introduced into the mold body for the partial shells, one at a time. The required local wall thickness is obtained by pressing the strands, using special pliers and by laying them down either standing up or lying down, depending on whether one desires a wall thickness which is greater or smaller than what would be obtained with the square strand (Figure 12).

The strand running lines marked on the mold body and the numbering system for the strands starting at the straight center strand, makes it possible to obtain any wall thickness variation, and it can be controlled during the manufacturing process of the shell. If the strands are applied with care, it is not necessary to do any more reworking of the hardened shells except to flatten the separation surfaces.

It is known that the surface quality corresponds to that of the mold, and that the product has the true shape, is free of waves, and is smooth.

Figure 12. Diagram of the strand paths and lines of constant wall strength in the casting die for manufacturing one-half of the shell for a rotor made of glass fiber-reinforced plastic.

1- strand lines; 2- separation surface; 3- cross section N-N; 4- lines of constant wall thickness d; 5- shell thickness d; 6- position width b; 7- imbedded strands; 8- smooth surface of the die cavity; 9- artificial rock; 10- heating grid; 11- perforated sheetmetal support; 12- coolant.

In the case of large rotors, the strand is run from the edge of the mold to the connection flange, then over the connection bolt, and then back again to the edge of the mold. In the case of small rotors, the strand is applied double along its complete length and the loop is run over the bolt.

10. Design Examples

One of the many applications examples of the outlined experimental results and methods are the main and tail rotor of the Boelkow Heli-Trainers, as well as the helicopter B 103. The main rotor blade is 2.9 meters long and has no twist. It has a symmetric profile. The center of gravity offset is made small by concentrating the glass strands which take up the radial loads up to 22% of the blade chord. Also, a steel rope is imbedded in the nose of the blade as an additional mass balancing weight.

The blade connection flange is elliptical. The glass flange is cast and then pressed against an opposing flange of the construction. The attachment bolts are adapted as is the flange. After this process, no additional reworking is required.

The manufacture of the single blade tail rotor blade is especially simple. In this case, the strands were directed around a groove of the balancing weight and then next to the bolts of the attachment flange.

All of the blades have a thin glass cloth insert with linen structure as a covering layer and a carrier of the desired color. It is also intended to avoid heating of the pigmented resin by the sun. In the outer region of the blade where one could expect a drop erosion because of the high circumferential velocities, the profile nose is protected by a thin rubber layer which is glued on.

The manufacturing costs of the glass fiber rotor blades are much lower than those for blades made in the conventional way.

Compared with the only 3 m long and 9 kp helicopter rotor blades, the blades of the already mentioned 100 kW wind turbine have a rotor diameter of 34 m, which is the dimensions of large aircraft. The area density is 3.8% and the freely supporting blade length is almost 17 m. The blade weight is only 680 kp. The wall thickness of the supporting shells decreases continuously from the blade root to the blade tip from 24 to 4 mm. A polystyrene foam filling is used to protect the blade against buckling and transverse force transmission.

With the exception of the region of the blade root, the entire blades have laminar profiles. After three years of weather exposure, no noticeable surface damage has been observed. Prolonged storage times have not resulted in any creep under the influence of the weight of the blade.

The velocity ratio, the ratio of the tangential velocity at the tip of the blade to the incident velocity, amounted to about 24 for idling conditions, a value never reached before.

The many applications which are possible with these blades show that very often in research and development work, a side result becomes a main result.

11. Summary /381

Since fiber-reinforced materials are orthotropic and because unsaturated resins capable of polymerizing shrink during the hardening process and are used as imbedding masses, because they creep under loads and also have relatively low strength compared to the fibers, such composite materials can only compete with high quality light metals in those components which are stressed along one axis because of their shape or configuration.

It is easy to produce high glass content in the laminate during the drawing of rovings. This is done using step nozzles. Cloths and mats have disadvantages because of the weight-specific strength and stiffness and also because the possible glass content is limited.

The compression strength of strand-reinforced materials in the fiber direction reaches the values of the tensile strength if the force is introduced in a flawless way. The compression fracture is introduced by wave-like evasion of the elementary fibers.

In the case of oscillating loads, glass fiber reinforced resins behave very similar to metallic materials. Fracture starts with delamination phenomena parallel to the reinforcement fibers in both the static and dynamic load cases.

It has become possible to construct large rotor blades and blower buckets by making the connection members in the form of flanges, which are made up of a series of strand loops. The selection and control of the wall thicknesses are the result of the width variation of the strands during the formation process, during which they are pressed down flat and run out at the edges of the shells and at the separation cracks.

A number of design examples have been tested over extended time periods and have demonstrated the feasibility of the principle, which was first applied in the construction of a freely supporting blade of a wind turbine having a diameter of 34 m.

Discussion

Dr. Eng. K. Loeffler (Stuttgart): Have blades for axial compressors been made from glass fiber reinforced plastics? If so, it would be desirable to manufacture the hub required for support out of this material in order to save weight. This hub is essentially stressed by tangential stresses. Is it possible to produce such cylindrical bodies by spiral winding of the glass fibers?

Prof. Dr. U. Huetter: Blower buckets for axial compressors are already being made in various ways out of this material at the Haenle firm. These are compressor blades with lengths between 20 and 200 mm. Blower blades are already being manufactured for a cooling blower unit with considerably larger dimensions. Of course, it is possible to manufacture the hubs out of rovings. Even for these wound components, which are subjected to large centrifugal forces, the crack length represents a very important material property for the design weight. However, one must consider the fact that, in the case of components for which there is not preferred loading in one direction, smaller crack lengths must be expected. Quasi-isotropic glass fiber plastic combinations with flaws or multilayer strand reinforcements have, at the most, one-half of the crack length of orthotropic strand-reinforced materials.

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